The Human Powered Submarine Team of Virginia Tech

Propulsion System Design

Final Report

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VT
Phantom

Introduction

History

The Human Powered Submarine Team has been in existence at Virginia Tech since its conception in 1993. Since then, it has served as a way for engineering students from many different disciplines to implement design conception and realization. The first submarine built was Phantom I, a two-man submarine made of fiberglass. After construction was complete, Phantom I was ready for racing, but, unfortunately, suffered fatal problems come race time. The submarine team slowed down a bit after experiencing racing problems, but was revived in 1995 when design efforts for a new two-man submarine, the Phantom II, commence. The propulsion system consisted of a chain and gear drive system using an ultra-light helicopter tail rotor for a propeller. Although the team learned valuable lessons as a result of Phantom I's problems, Phantom II still experiences problems at races. After various parts of Phantom II are redesigned, it is once again ready for racing and proves that the redesign was well worth the time and effort. In 1997, Phantom II not only finishes its first race, held in San Diego, California, but comes in third. This success sparks yet another revival of the submarine team and design for the team's current project, the Phantom III, a one-man submarine, is started. In 1998, the plug for Phantom III is built and the hull is constructed. With so many past problems from which to learn, Phantom III promises to be the fastest and best-designed submarine the team has developed thus far. The current speed world-record is 7 knots.

Product Design Specification

The ultimate goal of the Phantom III's propulsion team is to propel the submarine to 7 knots and, thus, make it a formidable racing opponent and a possible world record holder. Of course, in order to achieve this lofty goal, the propulsion system must be well designed, in order to minimize losses associated with the system's components. The goal is to make the propulsion system as efficient as possible. The first step taken towards meeting this goal was to develop a design specification. The specifications for the propulsion system design follow.

Performance

The purpose of the *Phantom III*, Virginia Tech's one-man, human-powered submarine, is to win races. In building the propulsion system for the *Phantom III*, a common goal is to propel the vessel to greater than 7 knots, which would put it amongst the top competitors in the world. By minimizing mechanical losses and maximizing efficiency, the goal of propelling the submarine to greater than 7 knots can be wholly obtainable.

Reliability

From past experience with human powered submarine propulsion systems, it has been learned that chain drives become very unreliable when operated in water or installed incorrectly. For this reason the team has decided that no chain or belt drives will be used in the propulsion system design.

Materials

Due to the fact that the propulsion system will be used in saltwater, it is necessary that all of the system's components be corrosion-proof. For the reason that corrosion will have adverse effects on the system's performance, no corrosion susceptible materials are to be used anywhere in the propulsion system. The materials most likely to be utilized are aluminum, plastic, stainless steels, and fiberglass/epoxy composites.

Size

Limitations are placed on the size of the propulsion system by the non-circular cross-section of the hull (which is already built) and its curvature. Regardless of which kind of system is used (gear, chain, belt, or some combination of those options), the decision has already been made that the input of power from the person to the shaft will be in the form of cyclic motion. A minimum of 1-inch clearance between the body and the hull during stoking (pedaling) must be assured. This restriction also implicitly limits the size of the gearbox.

Weight

In order to obtain the maximum power from the system, the pilot's work must be minimized. Although the weight of the system has not been limited to a specific value, a goal of the propulsion team is to minimize the weight of the moving components in order to minimize the pilot's work. By doing so, the goal of 7 knots or greater will be all that more attainable.

Quality/Reliability

Again, the purpose of the *Phantom III* is to win races, but races cannot be won if all components of the submarine are not in full operation. For this reason, the goal is to build a reliable and robust propulsion system. A propulsion system failure is the last thing the pilot/stoker needs to worry about. Simplicity of the system, robustness of the design, and quality of manufacture will be the keys to the propulsion system's reliability.

Product Life Span

The life span of the propulsion system must be at least two years, with regular maintenance intervals.

Production Time

The system must be able to be manufactured and installed within five to six months as the submarine is expected to be ready to race by mid-March 2000.

Manufacturing Facilities

The system must be able to be produced using standard manufacturing techniques, either by the students in the college's student shop or at other contracted manufacturing facilities.

Testing

The system will be tested in freshwater environments to confirm that the design meets all of the set requirements and is robust and problem-free. Testing will also be used extensively to improve the performance of the design. These improvements will be made possible by observing the effects of changes in various design parameters. Saltwater testing will not be a set requirement.

Product Cost

By inviting sponsors to aid our efforts and by keeping the system simple, our goal is to keep the submarine's propulsion system at as low of a cost as possible. If the system is designed so that it can be comprised of mainly catalog ordered parts, a low cost propulsion system will be very attainable. The goal of the propulsion team is to keep the cost in the $2000-$3000 range. Low cost is one of the most important items in this Product Design Specification list.

Maintenance

Because the propulsion system may need to be repaired quickly before a race, easy maintenance is very important. Easy removal from the hull will prove to be very beneficial if something breaks. Therefore, a goal of the propulsion team is to design a propulsion system that can be bolted to an independent support structure, such as brackets or hard points fiber glassed into the hull. The gearbox and drive train are the most important items to make easily removable, due to the possibility of failure and the need for regular maintenance.

Documentation

Each student on the design team will maintain a logbook of their thoughts, ideas, and contributions to the design process as well as the minutes from the design meetings. Two reports will be submitted during the course of the semester. The first will be a progress report and the second will be the project final report. The Human Powered Submarine Team of Virginia Tech will also receive an instructional manual detailing proper care, maintenance, and operation of the propulsion system.

Design Progress

Basic Design

During the first couple weeks of the design process, a basic system design was agreed upon. This design included the following:

1. A direct drive system would be implemented using a set of bevel gears with a 3 to 1 ratio.
2. The bevel gears would be housed in a gearbox. The larger bevel gear would be mounted on a shaft that extended outside the gearbox (on either side) and the crank arms with pedals would be mounted on either end of this shaft. The smaller bevel gear would be mounted on a shaft that extended out the back of the gearbox, towards the stern of the submarine. See Figure 1, page 6.
3. The bevel gear shaft would be connected and aligned with the propeller shaft with some kind of coupling.
4. A conduit (a hollow piece of sturdy piping) would be used to support the entire system, with one end mounted to the transom and the other end mounted to the gearbox by welded flanges. The conduit would house the propeller shaft, the small bevel gear shaft, and their coupling. See Figure 2, page 6.
5. The transom would be reinforced with a sandwich-style build-up, using sturdy materials such as aluminum plates and laminated composite called Nomex. See Figure 3, page 7.
6. The system will be sealed airtight in order to increase the efficiency and life of the drive train. To keep the gearbox dry will require seals and a pressure system.
7. An efficient propeller, designed with the help of propeller designers and computer program~~ming.~~ s

existing

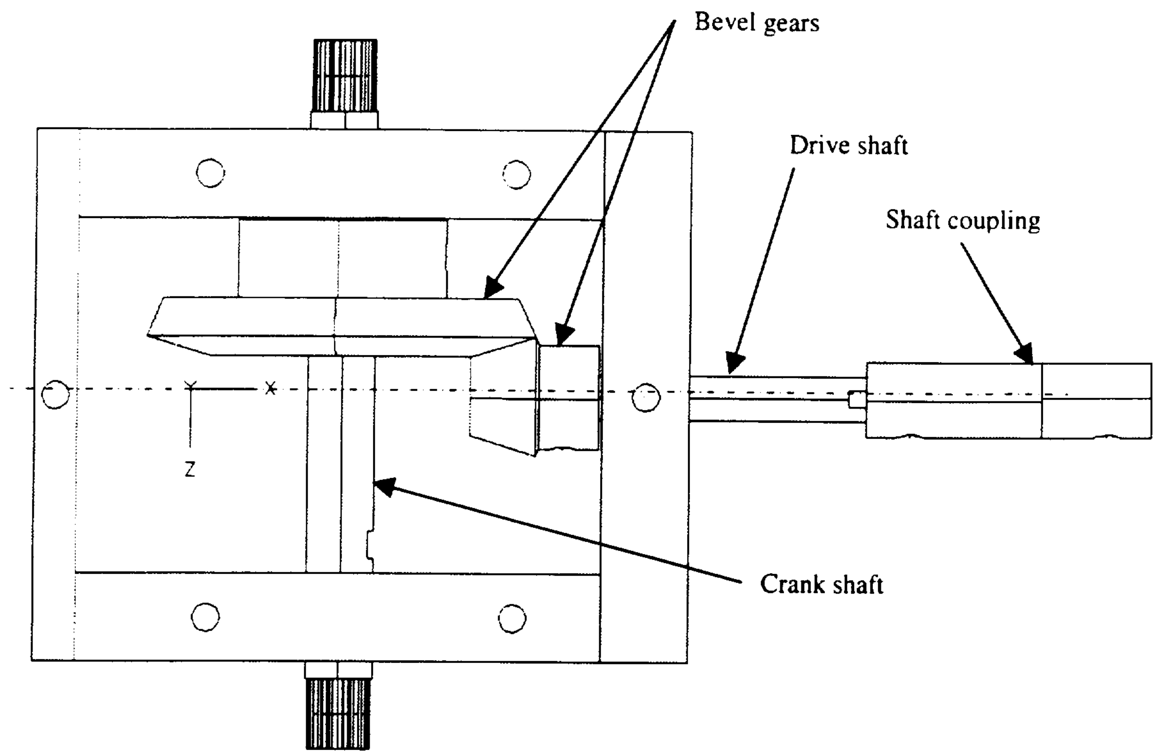

Figure 1. Top view of the gearbox showing bevel gears, shafts, and coupling.

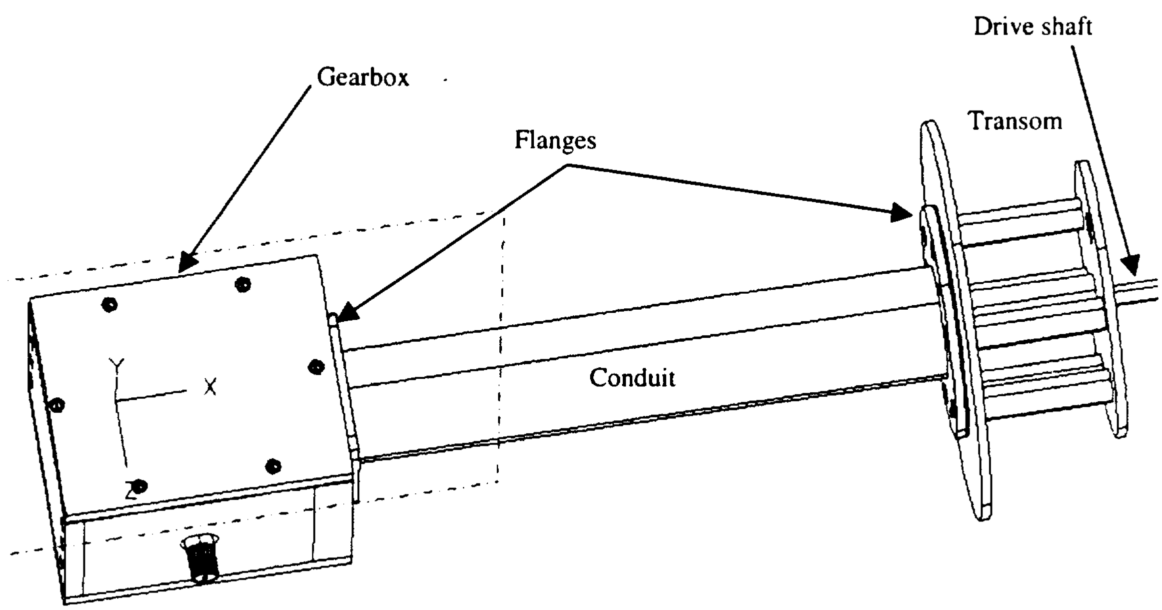

Figure 2. View of the conduit showing the attachment flanges and internal structure of the transom.

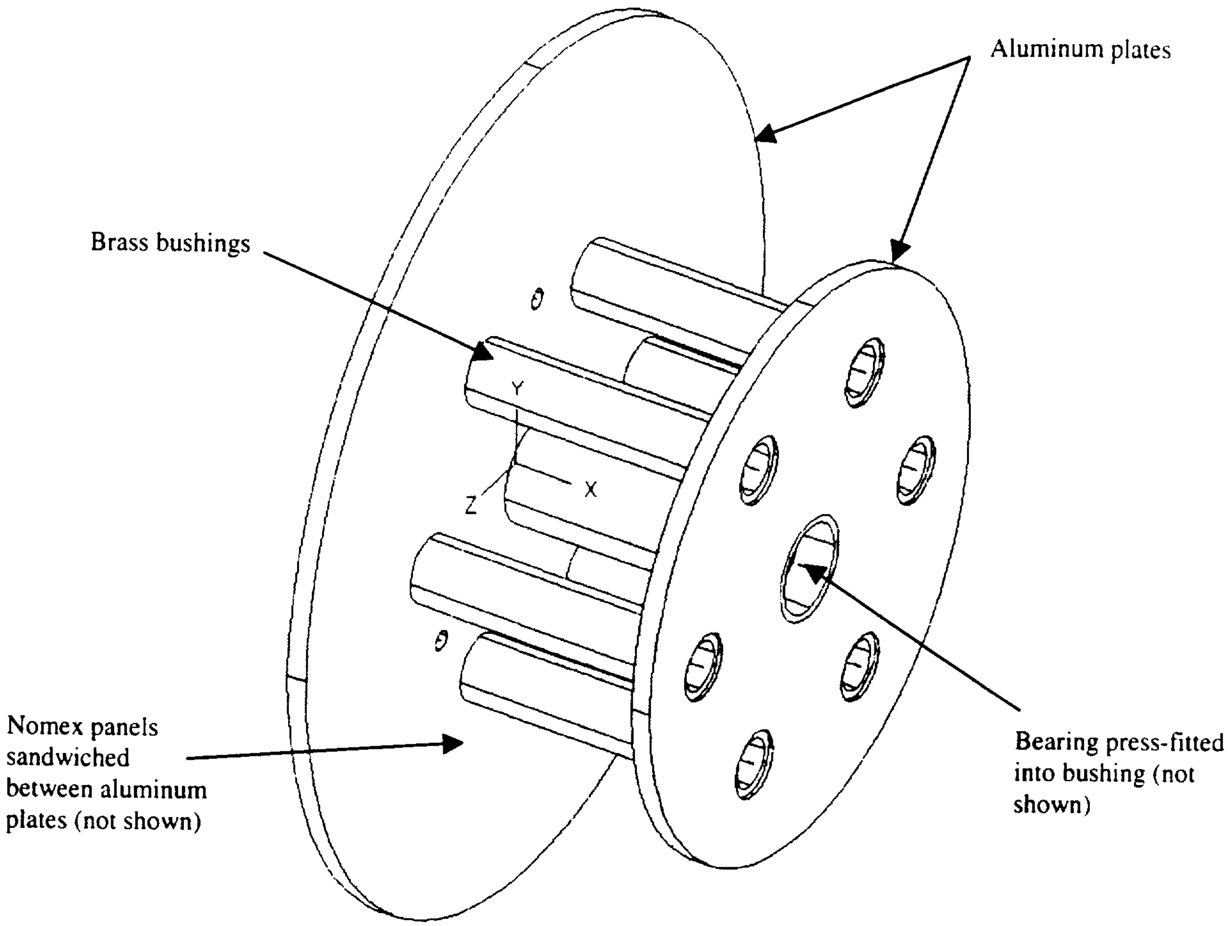

Figure 3. The internal structure of the transom.

Initial Considerations and Revisions

After the basic design was finalized, the team was forced to speculate, using its engineering knowledge, to make some initial guesses as to what would make the system most efficient. Regarding the bevel gears, it was thought that a set of spiral bevels gears would give the smoothest transmission of torque and, consequently, give a more efficient transmission of power. After contacting a number of gear companies, it was discovered that spiral gears do, in fact, provide smoother transmission of torque, but there would be no significant benefits with the low speeds at which the submarine would be running. Also, spiral bevel gears generate higher thrust loads, which would hinder the system more than smoother torque transmission would help. Hypoid bevel gears were also considered, so that the drive system could be offset slightly from the propeller shaft, theoretically making it possible to use longer cranks arms and, thus, see more torque from pedaling. This increase in pedaling torque, however, was determined to be negligible after some calculations. In the end, it was decided that a set of simply straight bevel gears would be used. Straight bevel gears transmit torque smoothly, especially at low speeds, and are readily available in variety of sizes and materials. Many different materials were considered for the bevel gears, most of them being high performance engineering plastics possessing high strengths and low weights and low coefficients of friction. Some of these are Nyloil, Delrin AF, and Acetron Acetyl. Although it would be ideal to make the gears out of one of these materials, bevel gears in the sizes which we need are not readily available in plastic. For the reason that it would be very expensive to purchase custom gears, especially made out of one of these very costly plastics, the team made the decision to by off-the-shelf stainless steel gears.

The coupling to be used was the next decision to be made. Originally, a spider joint was thought to be the best option. This type of coupling would pull apart easily, making the gearbox easily removable. In addition, the teeth on a spider joint are made of a high-density polymer, which help the joint account for slight misalignment between the shafts, yet still be strong enough to transmit the loads being applied to the system. After more research, however, the decision was made to use a polygon plunge joint (see Figure 4, page...). This type of coupling is also easy to separate, however, it can also transmit much more torque than the spider joint can, which means a smaller size can be used. With consideration for misalignment, it was decided that misalignment due to bending of the system need not be an issue. We determined the maximum deflection of the conduit to be very small (< .003", see equation 5, page 13), eliminating the need for a flexible coupling. Therefore, the only bending the system will see, if it sees any at all, will most likely be at the transom. If loads on the system do cause it to shift at the transom, the system itself (from propeller to gearbox) will remain in a straight line. Also, any minor misalignment between the shafts will be corrected by the ball bearings that will be supporting the two shafts.

Another item that presented itself was the option of using counter-rotating propellers, which are known to increase efficiency and, consequently, increase speed. Propellers can also effect the maneuverability of the submarine because the rotation of a single propeller has a tendency to "walk" the stern of the vessel sideways. Ultimately, a single propeller was incorporated into the design. The increase in efficiency seen with two propellers is not significant at low speeds and "walking" has never been a problem on the past submarines when only one propeller was used. Therefore, the added complexity of counter-rotating propellers was not outweighed by any additional benefits.

The material of the gearbox proved to be another item of concern. The gearbox needs to be very sturdy and non-corrosive, so the initial suggestion was to use aluminum. In addition to the previous two benefits, aluminum is also lightweight. With a little creative thinking, however, polycarbonate became the material of choice for the gearbox. Polycarbonate is also a very sturdy material and as strong as aluminum has a higher corrosion resistance than aluminum with the added benefit is that it is clear. If there is a difficulty with the drive system, the team will be able to pinpoint the problem before disassembling the gearbox.

Finally, the last decision to be made involved using a vertical support at the free end of the conduit. A vertical-mounting bracket would help the transom carry any loads seen from the propulsion system itself (the conduit, shafts, and gearbox) and also forces from pedaling during operation. Because current plans include reinforcing and overbuilding the transom, the vertical support is not currently included in the design. However, the final decision will be made after construction of the system is completed and the strength of the system is determined.

Final Design

Propeller

The propeller is the most crucial component of the propulsion system. Without an efficient and well-designed propeller, even the most innovative drive system cannot be fully effective. The propeller to be used will have 3 or 4 blades, and will be about 24 inches in diameter. One propeller designer stated that, "a 3 blade 24 (inches in diameter) wheel would be most appropriate and would yield about 70 pounds of thrust at 150 RPM and seven knots in a conservative wake field." Currently, designers from Bird-Johnson Company in Walpole, MA and Ellis Marine in Miami, FL, are aiding the submarine's propeller design. Also, a computer program, called Blade, developed by a Virginia Tech graduate student is being implemented. This program develops basic geometry (i.e. chord length, angle of twist, etc.) for a propeller blade with given inputs. The suggestions from propeller designers will aid the process of finding a propeller that fits the program's output. The final design of the propeller has not been determined at this point. This will be one of the first tasks undertaken when the team reconvenes next semester.

Transom, Shafts, Coupling and Conduit

The propeller shaft will run through the transom of the submarine. In order to carry the load of the system, the transom will be reinforced with layers of aluminum plates and Nomex honeycomb. Because the transom will be very difficult to model and an accurate strength cannot be calculated the goal is to over-design the transom so that it will withstand any unforeseeable forces.

The transom will be constructed by sandwiching layers of Nomex panels between two aluminum plates which are cut to fit into the back of the submarine. Increasing the distance between the aluminum plates to 4 inches and filling this space with Nomex panels will increase the stiffness of the structure. Brass bushings will be press-fitted into the transom in order to seal any holes which must pass through the transom and prevent water from seeping into the structure. See Figure 3, page 7.

A ball bearing will be press-fit into the reinforced transom in order to support the propeller shaft. A stainless steel thrust bearing will be mounted at the transom to transfer the thrust loads generated by the propeller to the submarine hull. A lock collar will then be used at the transom on the outside of the submarine to avoid axial movement of the shaft. The propeller shaft will extend forward and meet the bevel gear shaft, which will extend aft from the gearbox.

Several couplings were considered for the design. When the decision was made that a flexible coupling was not needed, the team first investigated the possibility of using a spline-type joint as the shaft coupling. A spline joint would allow the gearbox to be easily removed from the submarine and would also isolate the bevel gears and associated components from the thrust loads generated by the propeller. The problems seen with a spline joint though were the cost and difficulty in machining and limited torque capacity. Upon further investigation, another option was found in the form of a polygon coupling. Polygons are used in similar applications as splines, but have higher torque capacities. This alternative was all but locked into the design when a major producer of polygons showed interest in sponsoring the team. This coupling is designed to be attached to the drive shaft by means of a key and setscrew, similar to the bevel gears. See Figure 4 for a drawing of the polygon coupling.

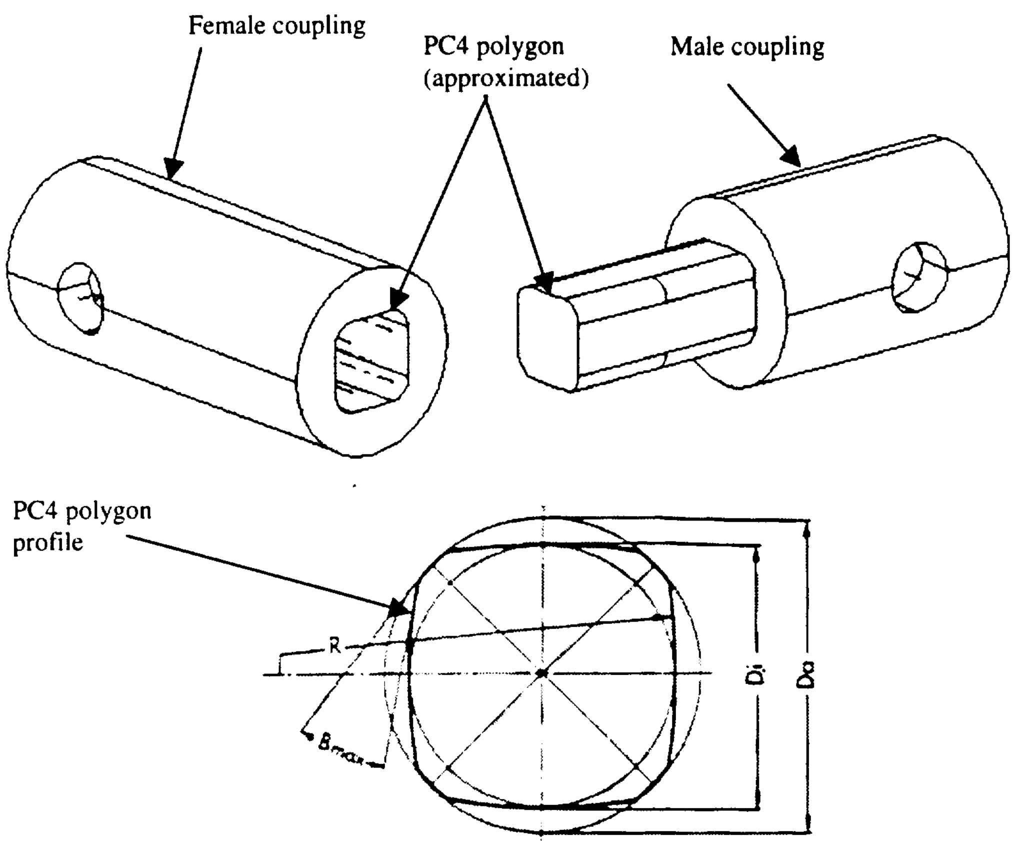

Figure 4. A CAD representation of the polygon coupling and the actual PC4 polygon profile.

The two shafts and the coupling will be housed in a conduit, which will be Schedule-40 steel piping with a 2.5 inch nominal diameter. The conduit will be connected to the transom by means of a circular flange with 6 bolts that will go all the way through the other side of the transom. The other end of the conduit will be connected to the gearbox by means of a square flange with 4 bolts. Each of these flanges is sealed to its mating component with a gasket in order to seal water out of the system. See Figure 5 for a detail of the conduit.

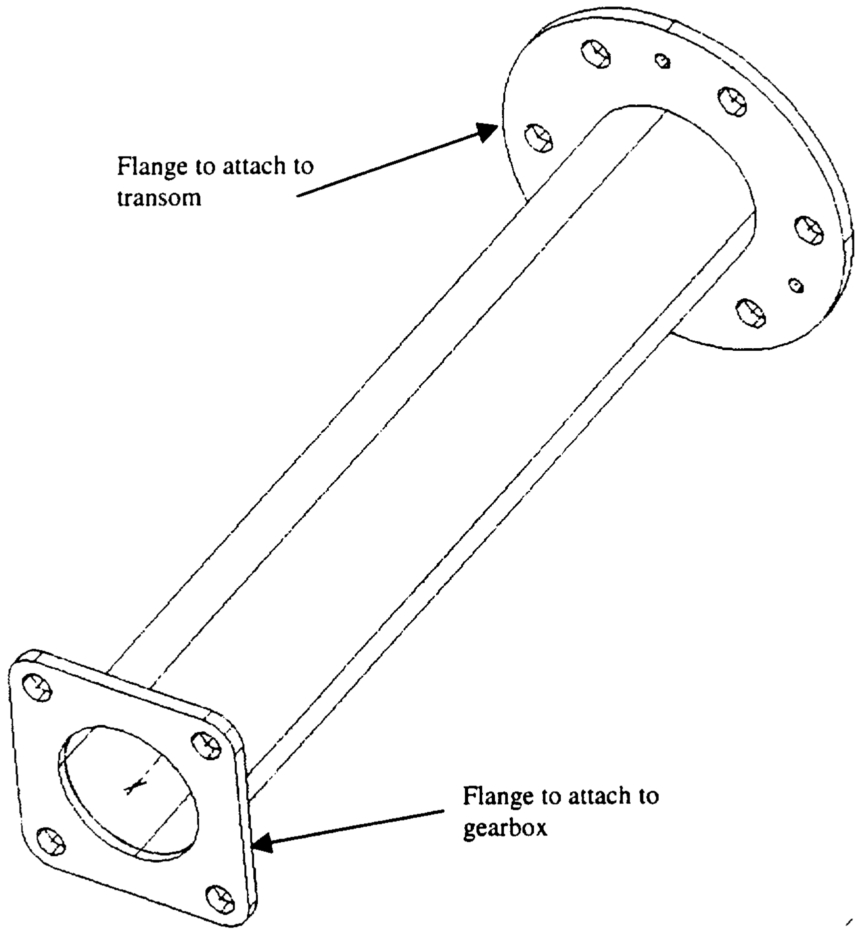

Figure 5. Drawing of the conduit showing the flanges.

Gearbox and its Components

The gearbox itself will be made of polycarbonate held together by machine screws and urethane adhesive. A ¾ inch diameter stainless steel crankshaft will run through the gearbox, from one side to the other and will have the crank arms with their pedals attached to either end. The crank arms will have a teardrop-shaped cross-section to make them as hydrodynamic as possible and they will be connected to the crankshaft with a spline and a small screw, for easy removal. The crankshaft will be supported at either end with bearings that will be press fit into the sidewalls of the gearbox. Plans for the gearbox include making it watertight, so o-rings between the inner race of the bearings and the shaft and also between the outer race of the bearings and the polycarbonate will be used. Lock collars will be put on the shaft and will fit snugly against the inner race of both bearings, in order to prevent any axial movement of the shaft. See Figure 6, page 12 for details of the internal layout of the gearbox.

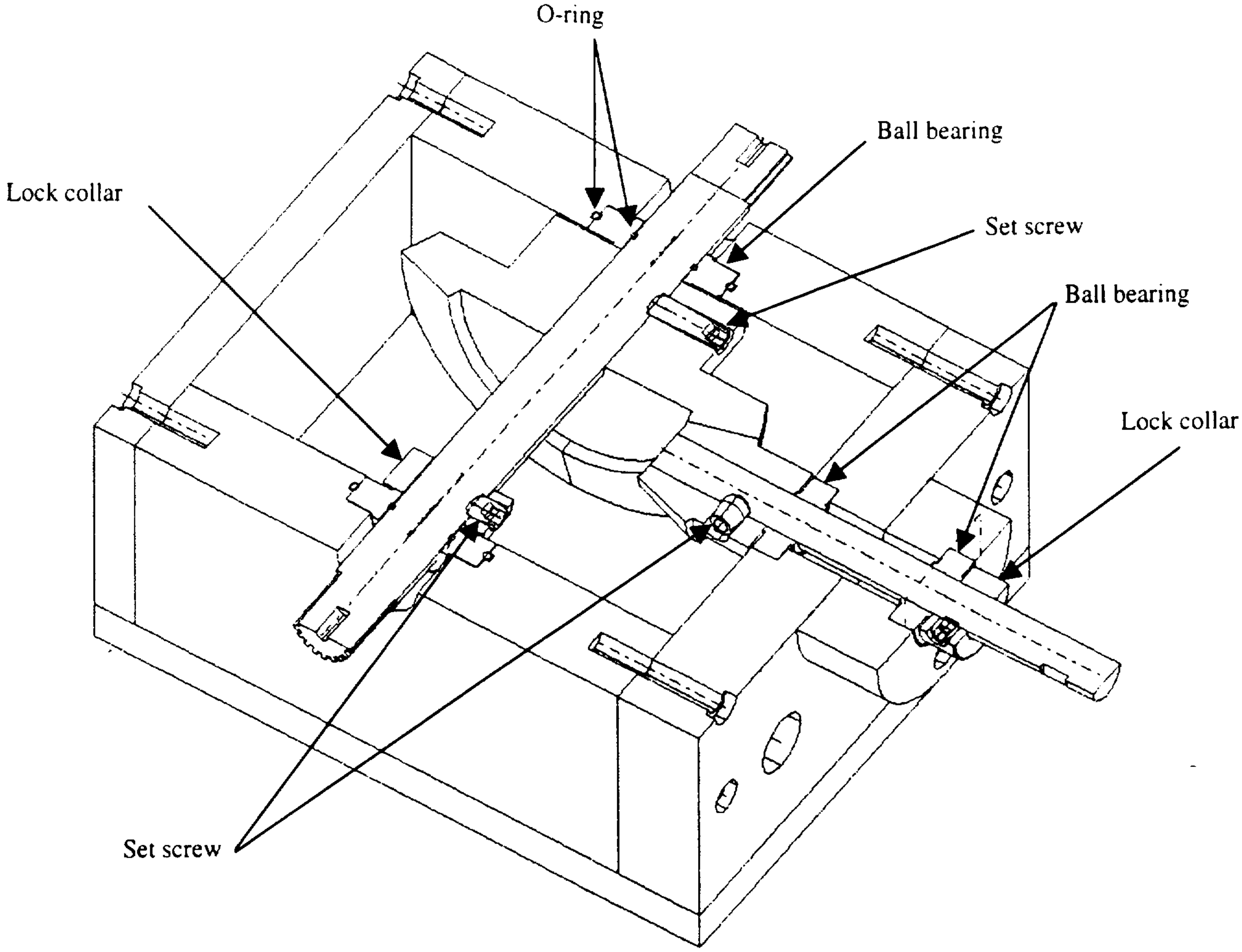

Figure 6. A section view through the gearbox showing all of the components.

The larger of the two bevel gears (3:1 ratio) will be fitted onto the crankshaft and will be driven by the pedaling motion of the submarine pilot. The smaller bevel gear will be mounted to the ½ inch diameter driveshaft that extends out of the back of the gearbox. Both of the gears will be secured to their shafts with a keys and setscrews. Lock collars will also be incorporated into the design to restrain axial motion of the shafts.

In order to increase the life of the drive train components, the gearbox is designed to be easily dissembled from the hull and all of the components removed. This is accomplished by first removing the gearbox from the conduit by removing the four bolts which hold it to the conduit flange. With the gearbox out of the hull, the top of the gearbox and the gasket under it are removed by unscrewing the six socket head cap screws holding them on. The two bevel gears and the lock collars are loosened from their shafts by unscrewing the setscrews holding them to the shafts. The shafts can then be slid out of the gearbox and the bearings can be removed from the gearbox walls. All of these components (including the shafts) will then be placed into a bin and coated liberally with penetrating rust inhibiting lubricant in order to protect them and increase their life. This bin will be sealed to protect the components from the environment and store them until their next use. This method can be used to remove the drive components from the submarine after each race, or whenever the propulsion system is not in use.

Detailed Design

By this point the team had made most of the decisions concerning the placement and orientation of all of the drive components, but the components would still need to be sized in order to finalize the design. The components must be designed to operate reliably under the maximum loads that will be applied to it without failing. In order to determine the stresses on the components, a maximum applied load had to be determined. It was the team's opinion that a maximum applied force of 150 lbf on one pedal would be a conservative estimate. This number was chosen because it is the average weight of the likely pilots and it is unlikely that the pilot could apply a larger force. Because the pilot's feet will be clipped into the pedals, the decision was made that a force of no more than 75 lbf could possibly be applied to the opposite pedal in the opposite direction of the 150 lbf force. These loads assume that the system is in a state of static equilibrium and that the pilot is applying as much load to the pedals as possible. Because this will be the worst load case, a dynamic load analysis of the system was not performed. The dynamic system loads under normal operation will be an order of magnitude less than the maximum static load, so the system was designed around a static failure mode.

Once the maximum operating load applied to the system was approximated, the stresses in all of the components could be determined and factors of safety calculated. The maximum load was increased by a factor of 2 in order to compensate for any impact loading which may occur during the operation of the system.

The first component to be designed was the conduit. Initially the conduit was to be made of aluminum, but the decision was later made to go to steel because of its increased strength and rigidity. The small cost in increased weight is outweighed by the gains of greater availability of material and easier manufacturability. The conduit and welded flanges will be well coated to prevent any corrosion. The stress in the conduit is a combination of compressive stress and bending stress. The calculations follow.

Conduit Stress Analysis

$$\sigma_C = \frac{P}{A} \quad (1) \qquad \sigma_B = \frac{Mc}{I} \quad (2) \qquad \sigma_T = \sigma_C + \sigma_B \quad (3)$$

$$\sigma_T = \underset{\uparrow}{2} * \left(\frac{(150+75)}{1.743} + \frac{900*1.438}{1.559} \right) = 1832\,psi \qquad FS = \frac{S_y}{\sigma_T} = 21.8 \quad (4)$$

Impact effect

$$\delta = \frac{Ml^2}{4EI} \quad (5) \qquad \delta = \frac{2*900*15.5^2}{4*30*10^6 1.559} \qquad \delta = 0.0023 inches$$

Your Moment 13 a twisting Moment, not Bending? OK I was thinking "Bike" position Not [illegible]

For a 2½ inch (nominal) diameter steel conduit 15½ inches in length with a loading of 450 lbf (axial) and a 900 lbf*inch moment applied to the end. The moment was calculated using a pedal-to-pedal distance of 8 inches.

$$M = Fl \qquad \textbf{(6)} \qquad M = (150+75)*4 = 900 lbf*in$$

Gear Stress Analysis

$$\sigma = \frac{2T}{\pi WYD^2} \qquad (7) \qquad \sigma_C = \frac{2*3100}{\pi*0.6*0.100*1.5^2} = 15{,}045 psi$$

S_y for 303 ? 440C ?

T :Input Torque
W: Face Width
Y: Form Factor
D: Pitch Diameter

$$FS = \frac{S_y}{\sigma} = 2.3$$

For the smaller bevel gear in 303 stainless steel

$$\sigma_C = \frac{2*3100}{\pi*0.6*0.146*4.5^2} = 1145 psi \qquad FS = \frac{S_y}{\sigma} = 30.6$$

For the larger bevel gear in 303 stainless steel

The applied torque was calculated using a crank arm length of 175 mm.

$$T = Fr \qquad \textbf{(8)} \qquad T = (150+75)\left(\frac{75}{1000*.0254}\right) = 3100 lbf*in$$

? with 175, still do B-1 2 ? is this the should load factor of 2? (here also)?

Shaft Stress Analysis

Crank Shaft:

$$\sigma = \frac{Tc}{J} \qquad \textbf{(9)} \qquad \sigma = \frac{3100*0.375}{0.0311} = 38{,}520 psi$$

$$FS = \frac{S_y}{\sigma} = 1.8$$

For a ¾ inch shaft in 440C stainless steel

Drive Shaft:

$$\sigma = \frac{Tc}{J} \qquad \sigma = \frac{1}{3} * \frac{3100 * 0.375}{0.0311} = 43{,}330 psi$$

$$FS = \frac{S_y}{\sigma} = 1.6$$ For a ½ inch shaft in 440C stainless steel

In order to protect all of the expensive components of the drive system from overload, the key which transmits torque between the larger bevel gear and the crankshaft is designed to fail at a lower load than the rest of the system. Details follow.

Key Design

$$\sigma = \frac{P}{A} \qquad \sigma = \frac{T}{rlw} \quad \textbf{(10)} \qquad \sigma = \frac{3100}{0.375 * 0.5 * 0.1875} = 88{,}120 psi$$

$$FS = \frac{S_y}{\sigma} = 1.1$$

Therefore the key will fail at the maximum design load. All of the other components are designed with factors of safety greater than 1, so that they will fail after the key.

Future Plans

The team did not accomplish all of the things which it set out to do during this semester. As a result, some tasks have been pushed off to next semester to be completed. These tasks will have to fit in with those which have already been planned for next semester which means that the team will have to be organized and structured in its approach to the completion of the project. A preliminary list of tasks for next semester (in approximate order) follows.

1. Assemble transom into Phantom III hull.
2. Finish propeller design through industry contacts and computer simulation.
3. Arrange for propeller manufacture.
4. Design pressure system.
5. Order all drive train components.
6. Machine/manufacture all components.
7. Assemble all components into hull.
8. Test drive system in closed-water environment (War Memorial pool).
9. Redesign system based on evaluation of test results.
10. Modify system based on redesign.

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January 31, 2000

Mr. R. Todd Lacks
Grant Officer
NASA Langley Research Center
Mail Stop 126
9A Langley Boulevard, Building 1195B
Hampton, VA 23681-2199

Subject: Final Report for NAG-1-2053

Dear Mr. Lacks:

Enclosed is a copy of a final report for the subject grant.

Do not hesitate to contact us if additional information is required.

Sincerely,

Bonnie Beasley

Bonnie Beasley
Contract and Grant Administrator

Enclosure

cc: Dr. Gary L. Farley, MS 266
CASI